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# Uranium Mining and Milling

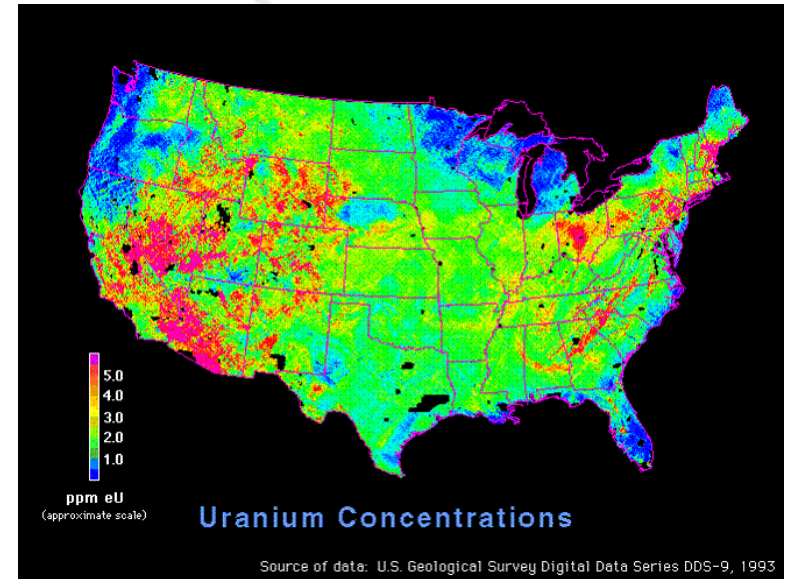
Pete Karpus

February 2017

# Uranium Mining

Uranium is naturally occurring at about 1.8 - 2.7 ppm in the earth's crust. U content in ores can range from ~0.02 to ~20 %.

Uranium ore can appear in many different forms, from the primary mineral uraninite, to the colorful secondary minerals shown below.



<http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/Uranium-Mining-Overview/>



Uraninite ( $\text{UO}_2 / \text{U}_3\text{O}_8$ )  
"pitchblende"



Torbernite  
 $\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12 \text{H}_2\text{O}$



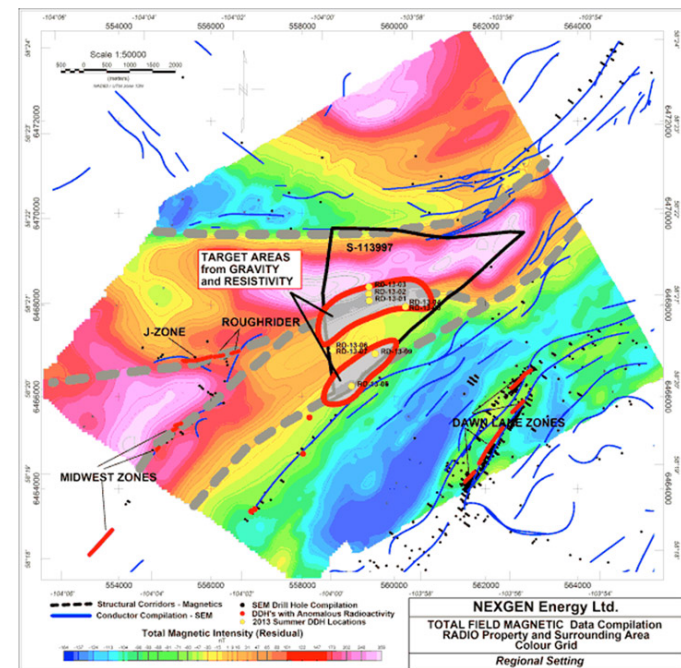
Carnotite  
 $\text{K}_2(\text{UO}_2)_2(\text{VO}_4) \cdot 3\text{H}_2\text{O}$   
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... 'ore', it could look just like a rock

# Uranium Mining

- Locating the Ore
  - Detecting Radiation
  - Magnetic Prospecting
  - Electromagnetic Prospecting
  - Gravitational Prospecting
  - Satellite Imaging
  - Geologic Field Sampling
- Mining Methods
  - Open-Pit
  - Underground
  - In-Situ Leaching



<http://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/mining.html>

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# Establishing a Mine

- After deposits are located, additional testing must be done to ensure it will be profitable
  - Drilling is done for samples
  - Environmental concerns are considered
- Permits must be obtained through local government
  - Could take years to obtain
- Opening a mine and separation plant can cost from \$500 million to \$1 billion, depending on the location, element, ore grade, and a variety of other factors

<http://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/mining.html>

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# Uranium Mining: Open-Pit

- Open pit mining, also known as strip mining, is the removal of surficial soils and uneconomic rock to get at the ore below.
- Ore grades are normally less than 0.5%.
- This is type of mining is only possible if the uranium ore is near the surface
  - normally less than 400 ft deep

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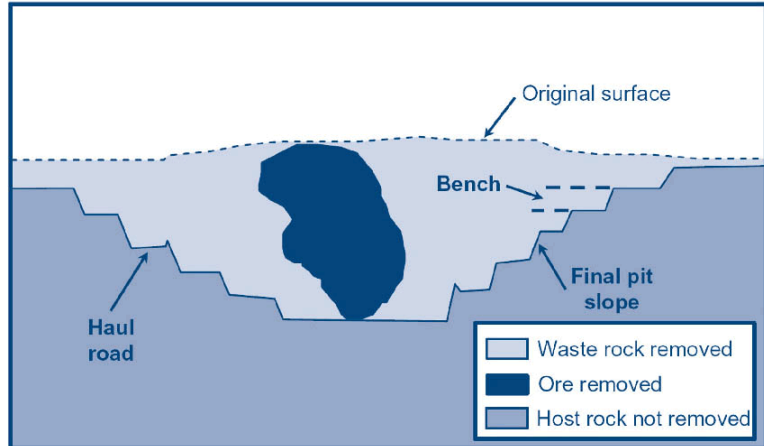
# Uranium Mining: Open Pit

Waste rock or overburden removed by blasting and usually is stored near the open pit.

Once the ore horizon is exposed, a series of benches or steps are cut into it to make removal of the ore easier.

Within the pit, depending on the size of the mine, there maybe one or more roads cut into the sides for the huge earth/ore haulers to navigate the area.

Pumps maybe utilized to dewater the pit.



<https://geoinfo.nmt.edu/resources/uranium/mining.html>

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# Uranium Mining: Open Pit

## ■ Pros

- Less expensive than underground mining
- Open-air ventilation
- New mines must follow much stricter environmental, safety and health guidelines than were in place during the last uranium boom.

## ■ Cons

- Huge footprint
- Waste rock can be enormous, economically challenging, and potentially hazardous to the environment
- Groundwater restoration can be costly
- Workers and nearby communities can suffer negative health impacts due to the dust, noise and other issues

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# Uranium Mining: Underground

- Underground mining is used to get at higher concentrations of uranium that are too deep to get at from open-pit.
- The ore is drilled, then blasted to create debris which is then transported to the surface, then on to a mill.

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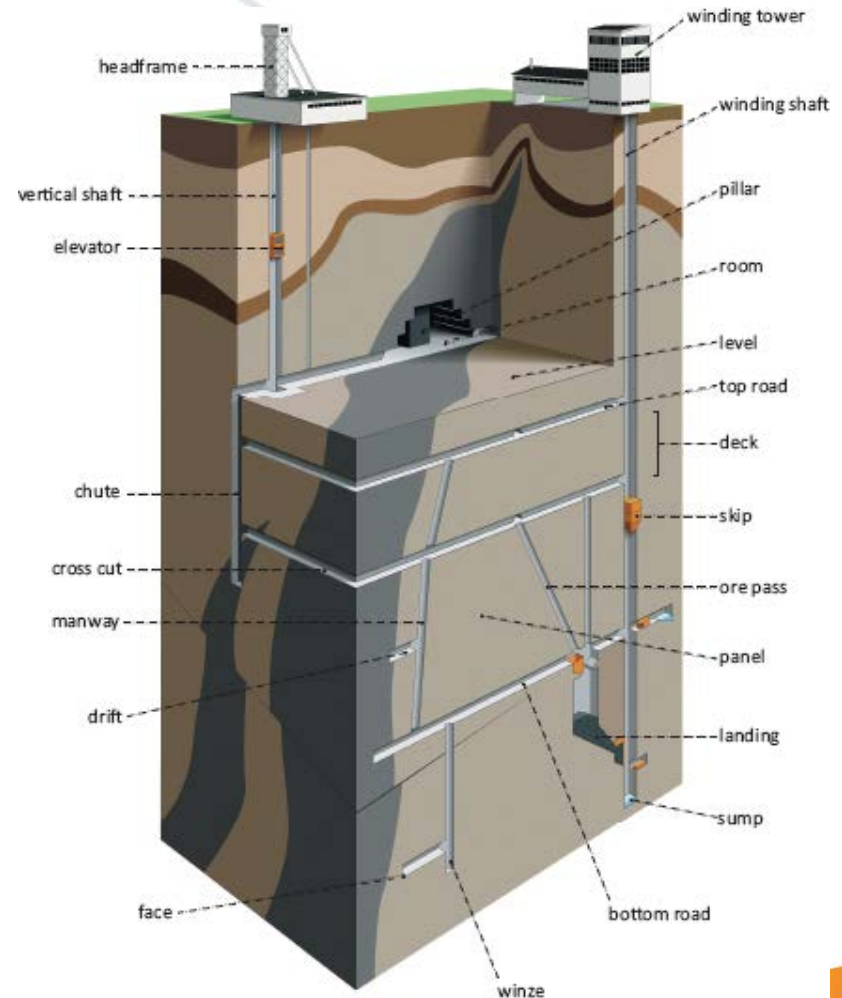
# Uranium Mining: Underground

First, miners dig vertical shafts to the depth of the ore

A series of horizontal tunnels are then cut to offer access directly to the ore and provide ventilation pathways.

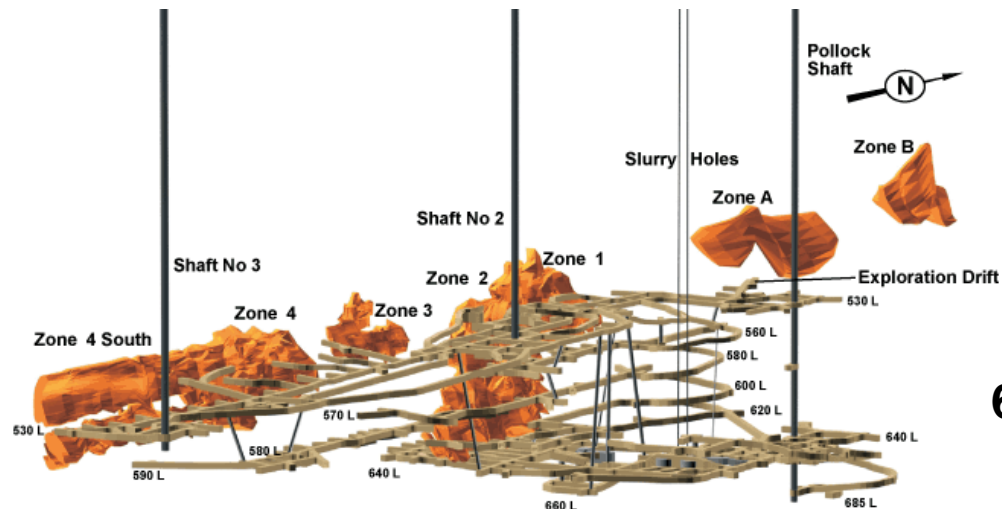
In most underground mines, the ore is blasted and hoisted to the surface for milling.

<https://cna.ca/technology/energy/uranium-mining/>



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# Uranium Mining: Underground



**685 meters deep  
(2247 feet)**

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# Uranium Mining: Underground

## ■ Pros

- Smaller footprint than open-pit mining
- Less waste rock than open-pit mining
- Advances in mining technology and safety monitoring greatly mitigates many of the radiation/health issues associated with earlier underground mining efforts.

## ■ Cons

- Expensive.
- Potential to seriously impact local aquifers and expensive to remediate.
- In old underground mines, dust, radon and diesel fumes were a serious threat to miners' health because of poor ventilation.

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# Uranium Mining: In-Situ Leach

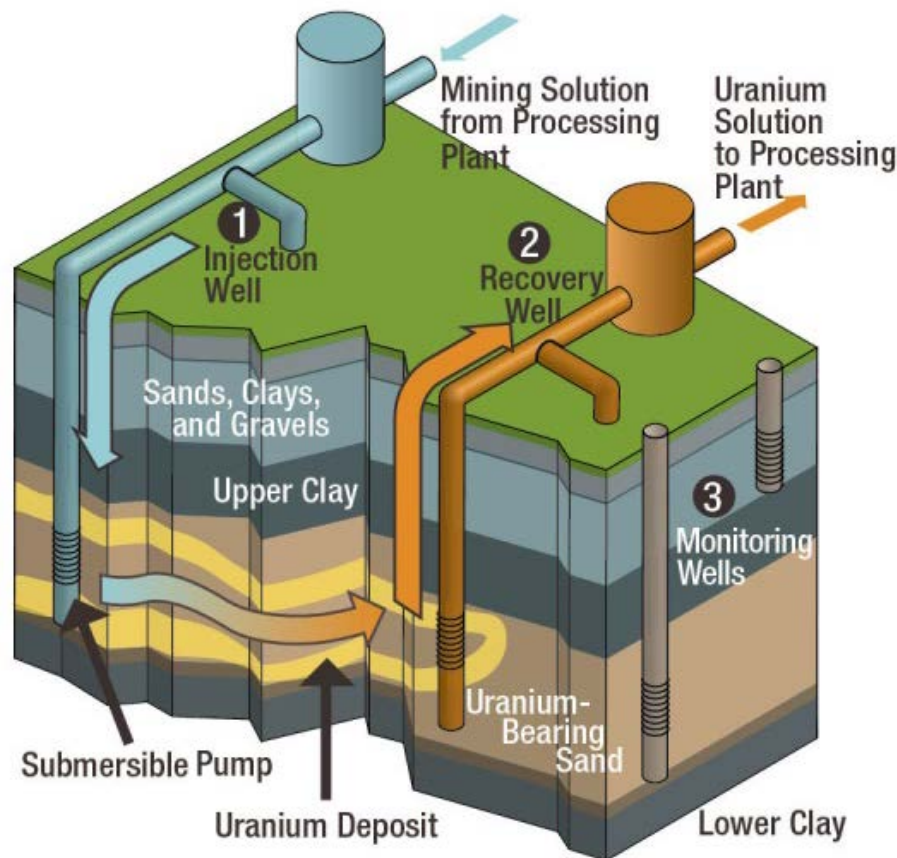
In In-Situ Leach Mining, holes are first drilled into the ore body

A leaching solution is then pumped into the deposit

The resulting solution with the extracted ore is then pumped to the surface.

There is no need for blasting as in open-pit or underground mining although hydraulic fracturing may be employed.

## The In Situ Uranium Recovery Process



[https://en.wikipedia.org/wiki/In\\_situ\\_leach](https://en.wikipedia.org/wiki/In_situ_leach)

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# Uranium Mining: In-Situ Leach

- Pros
  - Most cost-effective method
  - Little exposure of workers to radon
  - Energy efficient
- Cons
  - May produce significant pollution that requires extensive aquifer remediation
  - Requires a lot of local water

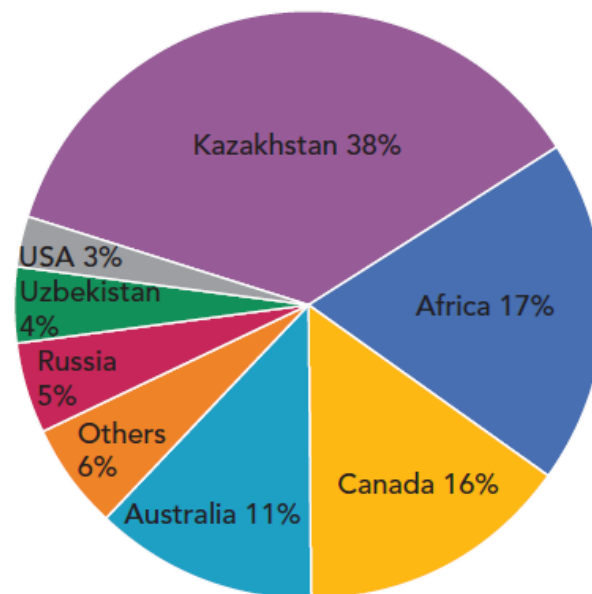
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# Uranium Mining

## Top Ten Uranium Mines 2014

Mine	Country	Main owner	Type	Production (tU)	% of world
McArthur River	Canada	Cameco	underground	7356	13
Tortkuduk & Moinkum	Kazakhstan	Katco JV/Areva, Kazatomprom	ISL	4322	8
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3351	6
SOMAIR	Niger	Areva	open pit	2331	5
Budenovskoye 2	Kazakhstan	Karatau JV/Kazatomprom, Uranium One	ISL	2084	4
South Inkai	Kazakhstan	Betpak Dala JV/Uranium One, Kazatomprom	ISL	2002	4
Priagunsky	Russia	ARMZ	underground	1970	4
Langer Heinrich	Namibia	Paladin	open pit	1947	4
Inkai	Kazakhstan	Inkai JV/Cameco, Kazatomprom	ISL	1922	3
Central Mynkuduk	Kazakhstan	JSC Ken Dala, Kazatomprom	ISL	1790	3
<b>Top 10 total</b>				<b>29,075</b>	<b>54%</b>

## World uranium production, 2013



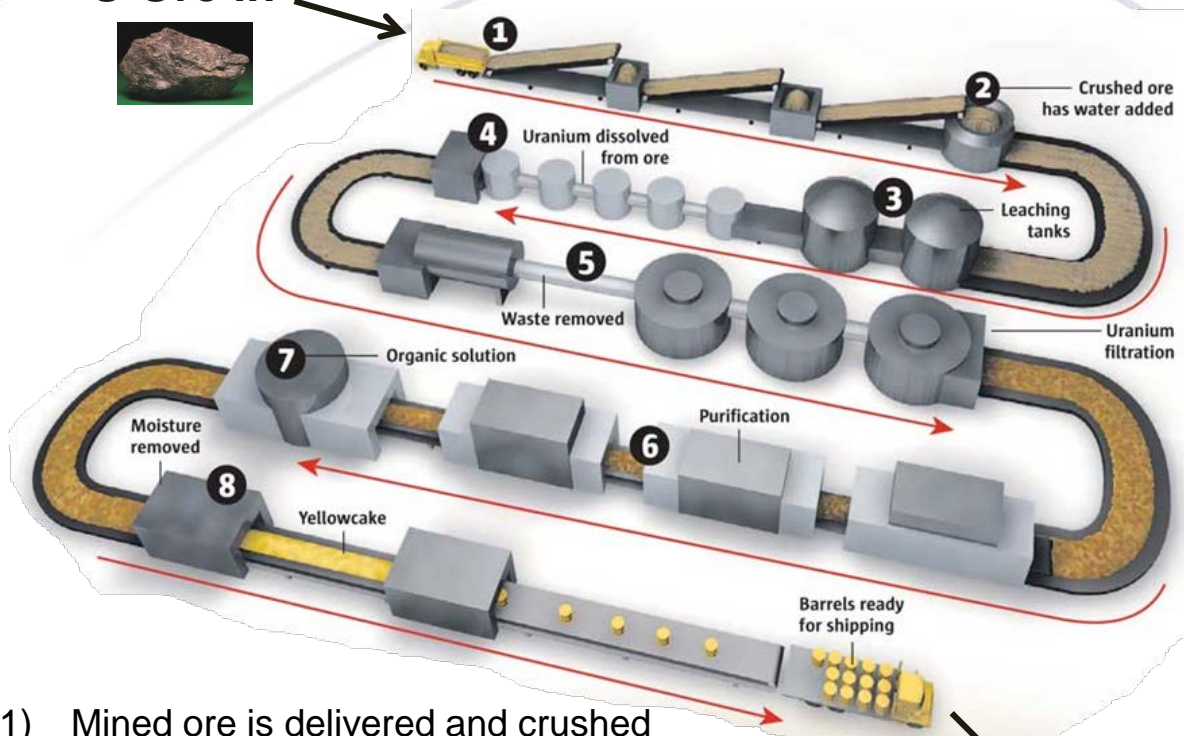
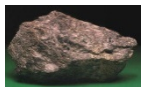
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# Uranium Milling

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# Uranium Milling Overview

U Ore in



- 1) Mined ore is delivered and crushed
- 2) Water added, ore ground into a fine sand (slurry)
- 3) Slurry pumped into leach tanks
- 4)  $\text{H}_2\text{SO}_4$  and  $\text{H}_2\text{O}_2$  added to dissolve U from ore
- 5) Waste is separated and stored in tanks
- 6) U purified and extracted using organic solution
- 7) U extracted from organic solution using ammonium sulfate
- 8) Excess moisture removed yielding  $\text{U}_3\text{O}_8$  "yellowcake"

$\text{U}_3\text{O}_8$  out  
(or  $\text{UO}_3$ )

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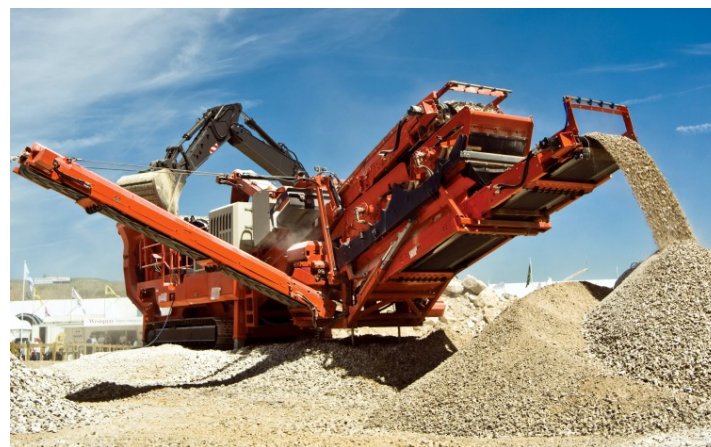


# Uranium Milling: Crushing

Uranium Ore from the mine is shipped to a nearby mill where it is crushed.

The resulting particle size must be small enough so that, when mixed with water it will flow under gravity.

There are a wide variety of crushing and grinding machinery options depending on the scale of the operation and the incoming ore particle size.



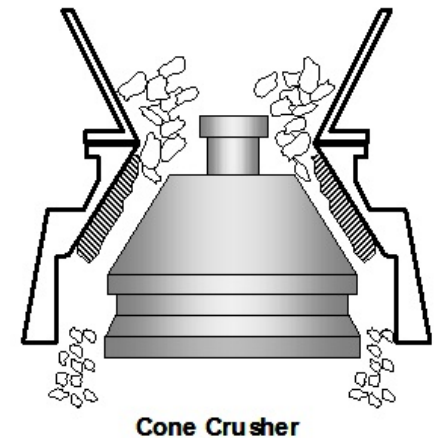
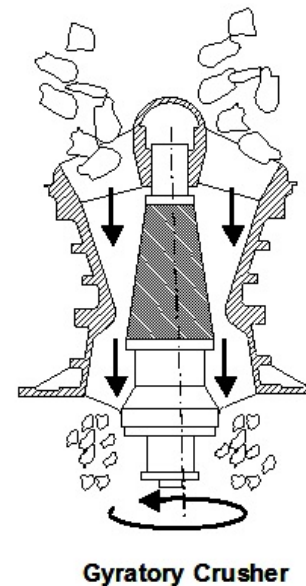
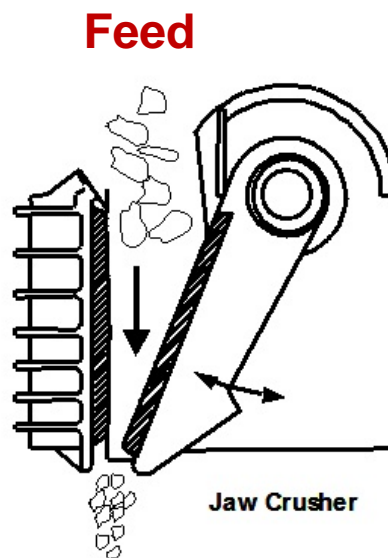
Mobile crusher by Sandvik (Sweden)

<https://www.iaea.org/newscenter/multimedia/photoessays/where-uranium-found-and-how-it-processed-nuclear-energy>

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# Crusher Types

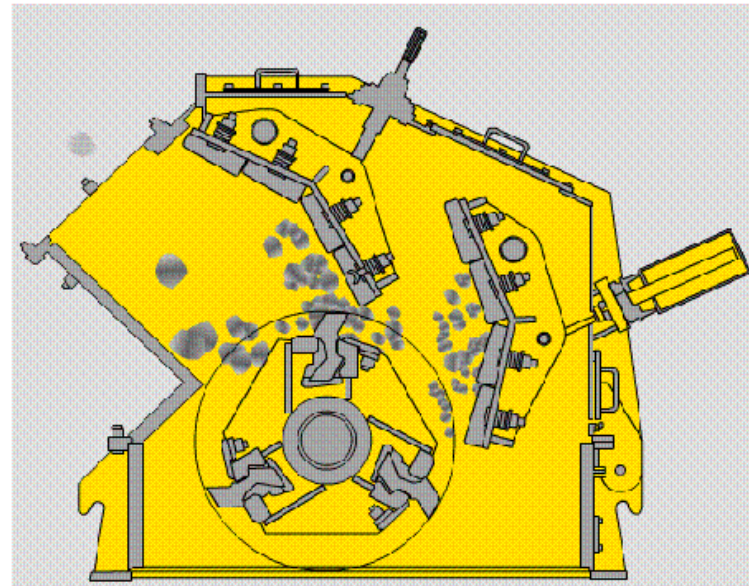
Jaw crushers are often in the early stages of the crushing and grinding operations.



Conical crushers may follow jaw crushers in a wet grinding operation to further reduce grain size.

# Example Ore Crusher

Stationary Impact crusher by Zenith (China)



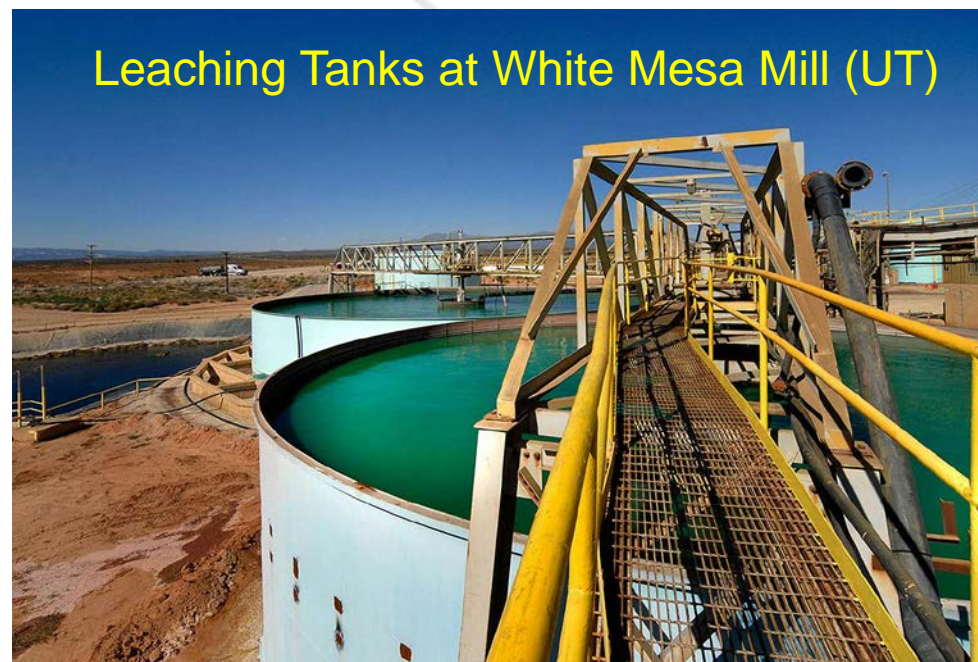
<http://www.continentalengineering.in/products/crushing/pf-series-impact-crusher.html>

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# Leaching of Crushed Ore

Leaching is the process of chemically processing the crushed uranium ore to extract  $\text{U}_3\text{O}_8$ .

Leaching is primarily done using sulfuric acid ( $\text{H}_2\text{SO}_4$ ) although alkaline leaching methods such as carbonate leaching have been employed.



The White Mesa mill near Blanding, UT is licensed to process an average of 2,000 tons per day of ore and produce 8.0 million pounds of  $\text{U}_3\text{O}_8$  per year. In full operation, the mill employs approximately 150 people.

# Chemistry Refresher

## ■ Acids

- Donate  $H^+$  ions (i.e. protons) or accepts electrons
- Taste sour and can burn your skin if strong enough
- E.g. Stomach Acid (HCL), Vinegar, Sulfuric Acid

## ■ Bases

- donate  $OH^-$  ions, or electrons ... or accepts protons
- Taste bitter, are slippery, and can burn your skin if strong enough
- E.g. ammonia
- Alkaline substances are bases that dissolve in water

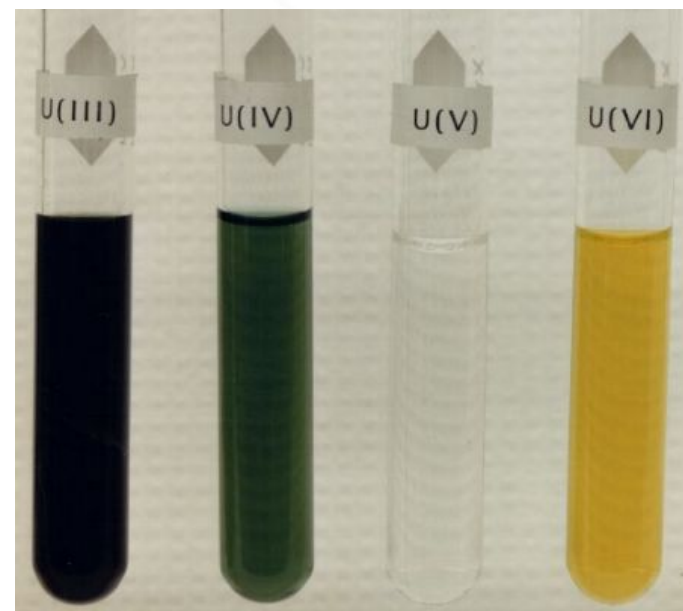
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# Uranium Oxidation Nomenclature

The **oxidation state**, is the hypothetical charge an atom would have in a purely ionic bond (no sharing of electrons).

Because of the structure of the oxygen atom, its outer (valence) shell needs 2 electrons to be complete. The oxidation state of oxygen in a compound is therefore -2. To make the compound  $\text{UO}_2$ , the uranium must give up 4 electrons, so its oxidation state in  $\text{UO}_2$  is +4. We write this as U(IV)

The most important oxidation states of uranium are the tetravalent U(IV) and hexavalent U(VI), and their two corresponding oxides are, respectively, uranium dioxide ( $\text{UO}_2$ ) and uranium trioxide ( $\text{UO}_3$ ).



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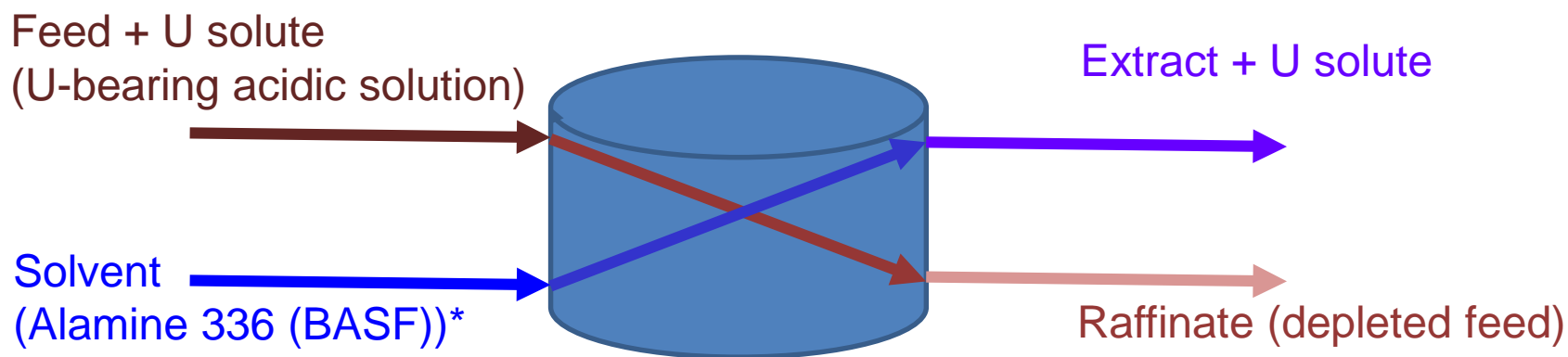
# Leaching to Extraction

- Hexavalent Uranium U(VI) is much more soluble in acids than Tetravalent uranium, U(IV)
  - Oxidizing agents can be added to convert U(IV) to U(VI)
- The  $\text{UO}_2$  in the ore then reacts with the sulfuric acid to produce  $[\text{UO}_2(\text{SO}_4)_3]^{4-}$
- The uranium is then extracted from the solutions by methods such as:
  - Solvent extraction
  - Ion exchange

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# Solvent (Liquid-Liquid) Extraction

- In general, solvent extraction is the separation of compounds based on their relative solubilities in two immiscible liquids (usually water and an organic solvent).



The solute is “scrubbed” then “stripped” from the extract

\*[http://www.mining-solutions.basf.com/ev/internet/mining-solutions/en/function/conversions:/publish/content/mining-solutions/download-center/brochures/BASF\\_Mining\\_Solutions\\_Flyer\\_Uranium.pdf](http://www.mining-solutions.basf.com/ev/internet/mining-solutions/en/function/conversions:/publish/content/mining-solutions/download-center/brochures/BASF_Mining_Solutions_Flyer_Uranium.pdf)

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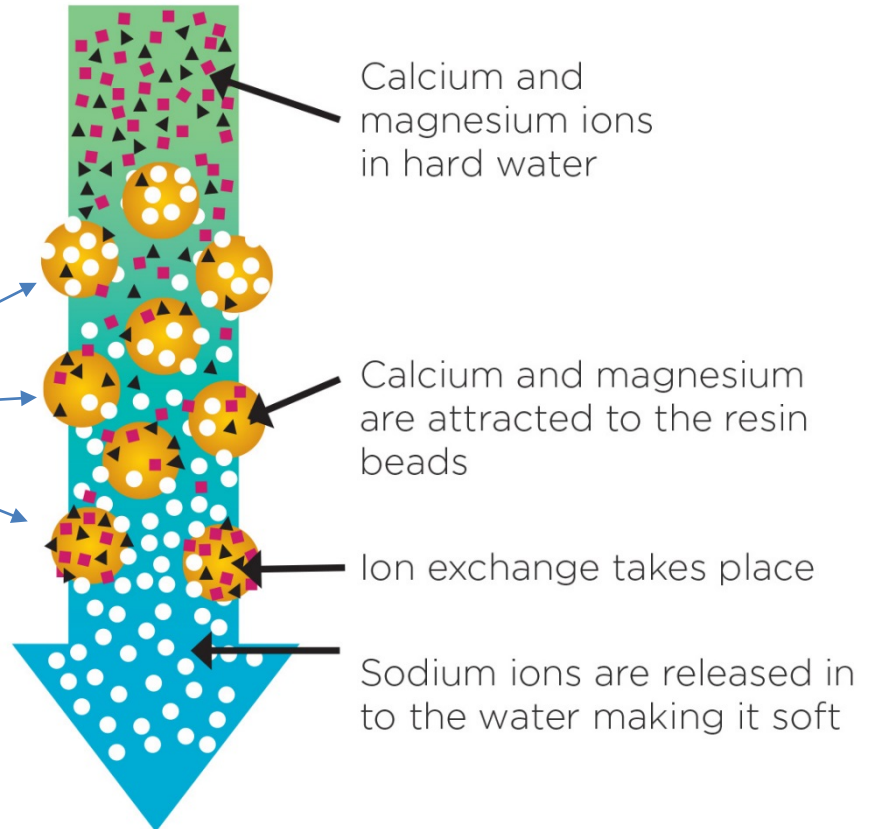
# Ion Exchange

When solutions of uranium containing an excess of free sulphuric acid are passed through a column of strong base ion exchange resin the uranium is sorbed by the resin.



Resin beads can be 'regenerated' using a solution that is highly concentrated in the regenerant

## Ion Exchange in Water Treatment

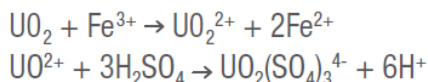


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# U Extraction Chemistry Summary

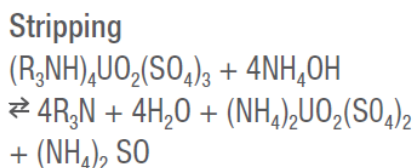
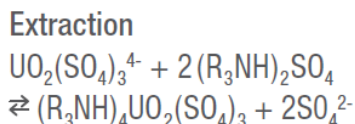
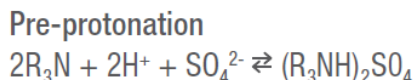
## COMMON CHEMISTRY FOR THE PROCESSING OF URANIUM

### H<sub>2</sub>SO<sub>4</sub> LEACHING



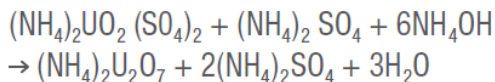
We oxidize uranium and then react it with sulfuric acid

### SOLVENT EXTRACTION (SX)



We then extract the uranium from the acidic solution and then strip it from the extractant

### AMMONIUM PRECIPITATION



The resulting uranium-bearing compound is then heated to produce U<sub>3</sub>O<sub>8</sub> (Yellowcake)

Ammonium Diuranate

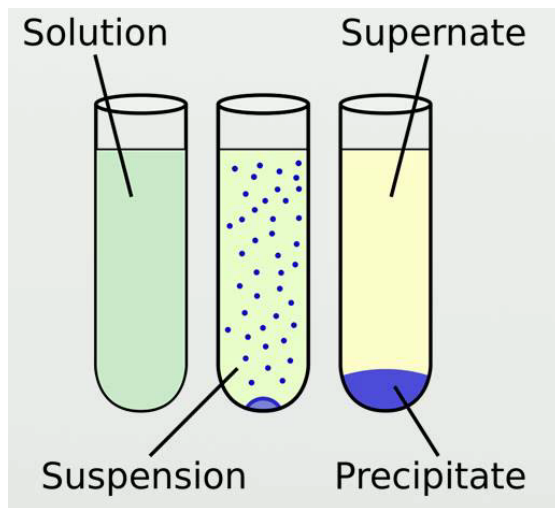
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\* Ibid (/BASF\_Mining\_Solutions\_Flyer\_Uranium.pdf)



# Precipitation and Calcination

- Precipitate: mix solutions and get an insoluble product
  - In this case, Ammonium Diuranate  $(\text{NH}_4)_2\text{U}_2\text{O}_7$
- Calcination: Precipitate is heated to  $> 600\text{ C}$  to make  $\text{U}_3\text{O}_8$



# Packaging and Shipment

- Uranium Oxide Concentrate or yellowcake is shipped from the milling facility to a 'conversion' facility usually in 55-gallon or 200-L drums
- Tens of drums may fit on a standard transport vehicle



Due to the low-level of radiation or usefulness of the material, the drums may be stored in standard shipping containers.

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# Summary

- The beginning of the nuclear fuel cycle is with mining and milling
- These two stages may take billions of dollars invested and applied over a multi-year period before any product is redeemed

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